55th Karpacz Winter School of Theoretical Physics and ChETEC COST Action CA16117 Training School – "Nuclear astrophysics in the multi-messenger era"

Sunday 24 February 2019 - Saturday 02 March 2019

Artus Hotel

Lecturers and topics

Physics of binary neutron star mergers

The very first detection of gravitational waves from a neutron star merger and accompanying electromagnetic emission marks a breakthrough in astrophysics. Already this single event has provided many new insights into astrophysics and many fields beyond astrophysics. An overview will be provided about the physics of neutron star mergers in general and the different implications of the first unambiguous detection of such an event in August 2017. The lectures will discuss in more detail possibilities to infer unknown properties of high-density matter and stellar parameters of neutron stars from gravitational wave measurements of compact star mergers. I will also describe the process(es) of mass ejection from neutron star mergers and their remnants, which is responsible for the formation of heavy elements through the rapid neutron capture process and for electromagnetic emission in the optical.

Nucleosynthesis in stars and in the big bang – the seeds for the r process

After the creation of the first three elements hydrogen, helium, and lithium in the Big Bang, most of the light elements up to iron are synthesised in nuclear fusion processes during hydrostatic stellar burning. These fusion processes set the stage for further neutron capture processes, among others. Thus their precise rates affect the abundance patterns of all nuclei, not only the light ones. Hydrostatic stellar fusion processes usually take place at energies well below the repulsive Coulomb barrier, making direct measurements challenging to perform. Experiments with high-intensity stable-ion accelerators in low-background, underground sites are a favoured approach to study a number of crucial fusion processes. The lecture will review the astrophysical sites, the relevant nuclear physics state of the art, and give an outlook on needed future progress.

Observing cosmic gamma-rays

Gamma rays are created in cosmic sources wherever high-energy interactions involving nuclear or cosmic-ray level energies are involved. Particle acceleration up to relativistic energies, i.e. beyond MeV energies characterising relativistic leptons/electrons, occurs most likely near compact objects and black holes as gravitational energy is released in large quantities, and relativistic pair plasma is one way how energy materialises; also, Fermi acceleration may be set up as relativistic outflows with variable outflow energies are created, such as assumed for gamma-ray bursts and AGN jets. Pair production limits energies to ~MeV in the co-moving system. Gamma-ray transients and bursts with such characteristic energies and with continuum spectra have been observed, and can be linked to different cosmic scenarios of black hole formation or flaring. Line emissions at characteristic gamma-ray energies from cosmic sources, on the other hand, display the action of nuclear reactions in cosmic sites. These result from nuclear transitions following radioactive decays or high-energy collisions with excitation of nuclei. The characteristic gamma-ray line from the annihilation of positrons at 511 keV falls into the same energy window, although of different origin. We present here the concepts of astronomical gamma-ray telescopes and cosmic gamma ray spectrometry, with the corresponding instruments and missions, followed by a discussion of recent results and the challenges and open issues for the future. Among the lessons learned are the diffuse\radioactive afterglow of massive-star nucleosynthesis in aluminum-26 and iron-60 gamma rays, which is now being exploited towards the cycle of matter driven by massive stars and their supernovae. Also, constraints on the complex processes making stars explode as either thermonuclear or core-collapse supernovae are being illuminated by gamma-ray lines, in this case from shortlived radioactivities from nickel-56 and titanium-44 decays. In particular, the non-sphericities that have recently been recognised as important are enlightened in different ways through such gamma-ray line spectroscopy. Finally, the distribution of positron annihilation gamma ray emission with its puzzling bulge-dominated intensity distribution is measured through spatially-resolved spectra, which indicate that annihilation conditions may differ in different parts of our Galaxy.

Hydrodynamics, turbulence and instabilities

These lectures will describe the physics of core-collapse supernovae with a focus on hydrodynamical instabilities. Instabilities, taking place in the inner 300 km during the collapse of the stellar core, are responsible for an asymmetric explosion and affect the kick and spin of the pulsar. Their imprint can be directly measured on the neutrino signal and the generation of gravitational waves. The dominant instabilities are

1. neutrino driven convection,
2. the standing accretion shock instability,
3. the corotation instability, and,
4. the magnetorotational instability.

Our understanding of these processes relies on numerical simulations and perturbative analysis. The lectures will also make use of the analogy with the dynamics of hydraulic jumps in shallow water and the experimental supernova fountain.

Gravitational wave astronomy of compact objects

1. Gravitational-wave (GW) emission and detection from compact objects
2. Physics of GW emission mechanisms in core-collapse supernovae
3. GW signatures from core-collapse supernovae

Heavy-element nucleosynthesis: the r process

The purpose of these lectures is to introduce our current understanding of heavy element nucleosynthesis in the Universe. In 3 lectures the basic nuclear physics, astrophysical and observational aspects will be introduced. They will be supplemented by tutorial/discussion sessions. The topics covered in the lectures are:

1. Astrophysical reaction rates. Nuclear reactions in astrophysical environments. Detailed balance. Nuclear statistical equilibrium. Neutrinos and weak processes.
2. Astrophysical sites. Basic ideas of stellar evolution. Astrophysical requirements for the *r*-process. Supernova vs compact binary mergers.
3. Observational signatures of the r-process. Chemical evolution. Electromagnetic signals of *r*-process. Compact binary ejecta. Simple kilonova light curve modeling.
4. GW170817 and its implications for the *r*-process. Electromagnetic signatures from GW170817. Does the *r*-process occur in the merger of two neutrons stars?

Literature

Y.-Z. Qian, *The origin of the heavy elements: Recent progress in the understanding of the r-process*, Prog. Part. Nucl. Phys. 50, 153 (2003)

M. Arnould, S. Goriely and K. Takahashi, *The r-process of stellar nucleosynthesis: Astrophysics and nuclear physics achievements and mysteries*, Phys. Repts. 450, 97 (2007)

F.-K. Thielemann, M. Eichler, I. V. Panov, and B.Wehmeyer, *Neutron Star Mergers and Nucleosynthesis of Heavy Elements*, Annu. Rev. Nucl. Part. Sci. 67, 253
(2017)

R. Fernandez and B. D. Metzger, *Electromagnetic Signatures of Neutron Star Mergers in the Advanced LIGO Era*, Annu. Rev. Nucl. Part. Sci. 66, 23 (2016)

Supernova neutrinos: What can we learn?

The detection of neutrinos from the next Galactic Supernova (SN) is considered one of the next frontiers of low-energy neutrino astronomy. In my lectures I will give an introduction on the physics potential of such an observation, where neutrinos play the role of astrophysical messengers. I will discuss how neutrinos would carry information about the mechanism of the SN explosion and how their detection would constrain non-standard physics scenarios. Particular attention will be devoted on the oscillation effects occurring in the deepest supernova regions, where the dense neutrino gas would exhibit fascinating collective effects.

Nuclear reaction measurements with at least one unstable partner

Most of the time, stars gain their energy from fusion of the very light left-overs of the Big Bang into heavier elements over long periods of time. The observation of radioactive isotopes in different regions of the Universe is an indicator of this ongoing nucleosynthesis. In addition, short-lived nuclei are often intermediate steps during the nucleosynthesis in stars. A quantitative analysis of these relations requires a precise knowledge of reaction cross sections involving unstable nuclei. The corresponding measurements are very demanding and the applied techniques therefore manifold.

Ion storage rings offer unprecedented possibilities to investigate radioactive isotopes in inverse kinematics. Coulomb excitation experiments give insights into time-reversed reactions. Surrogate reactions replace one or two unstable reaction partner with stable species. Recent experiments and possible future developments driven by the astrophysical needs will be discussed.